Recent strategies for 3D reconstruction using Reverse Engineering: a bird's eye view

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Abstract This paper presents a brief review of recent methods and tools available to designers to perform reverse engineering of CAD models starting from 3D scanned data (mesh/points). Initially, the basic RE framework, shared by the vast majority of techniques, is sketched out. Two main RE strategies are subsequently identified and discussed: automatic approaches and user-guided ones.

Keywords: Reverse Engineering; CAD reconstruction; Constrained Fitting.

1 Introduction

CAD models are nowadays fundamental in a great number of engineering fields and application. Within the design and fabrication processes of any mechanical part there are a number of steps where CAD models prove to be essential (e.g. sketching, 3D drawing, structural analysis). In the most advanced engineering companies and mechanical design studios, CAD models have become, in fact, practically indispensable, due to their great benefits. With this respect, noticeable examples are the reduction of the design phase duration and related costs, higher control of the project, and the access to a series of computer-aided tools (e.g. FEM, CAM) that allow a level of precision and efficiency otherwise impossible to reach.

In other words, CAD models have significantly shaped modern engineering and the whole product development process; therefore, lots of problems arise whenever the CAD model of a physical part that needs to be re-engineered, is not available.

Reverse Engineering (RE) aims at the retrieval/generation of the CAD model of a mechanical part, starting from 3D data directly measured on the physical object. The measurement can be done by means, for example, of a 3D scanner or a Coordinate-Measuring Machine (CMM) and typically results in a set of points or mesh, describing the object.

B. Eynard et al. (eds.), *Advances on Mechanics, Design Engineering and Manufacturing*, Lecture Notes in Mechanical Engineering,
DOI 10.1007/978-3-319-45781-9_84

The measured data implicitly contains information about the part's geometry, its surfaces and geometric features (e.g. planes, cylinders, spheres, etc. that may compose the object). Obtained data, however, are not useful for the designer as they stand, due to the following multiple factors: 1) measured data are always affected by an error, that generally can't be overlooked; 2) acquired points provide a discrete and not explicit representation of the original geometry; 3) the physical part has been fabricated with an imperfect process and has, therefore, inevitably diverged to a certain degree from its original design;

Summing up, acquired data is influenced by all the non-idealness of the fabrication and measurement process and necessarily needs to be elaborated to obtain a spendable result; to be useful for the designer needs, the obtained information is required to be channelled in an ideal mathematical representation of the object (a CAD model), attempting at the retrieval of the original design intent.

Finding a "good" geometrical representation, incorporating as closely as possible the original part design intent, is the ultimate result of the whole RE process. This topic has been recently addressed by a number of studies, and has received the attention of several software companies who released advanced RE-oriented CAD tools.

On the basis of the above considerations, the present work aims at identifying latest trends, innovations and limits of the RE process. To better understand the CAD reconstruction issue, a description of the basic RE framework is provided in section 2. In sections 3 and 4, two different RE approaches/tools are reviewed; due to their importance for designers, section 4 will be particularly focused on RE commercial software packages.

2 Basic RE Framework

In this section, the steps composing the basic RE framework (Fig. 1), usually shared by the vast majority of approaches and techniques, will be illustrated.

As previously hinted at, the typical RE process starts with the acquisition of 3D data describing the shape and dimensions of the physical object. This is typically achieved thanks to a 3D acquisition system (e.g. 3D scanner); other strategies [1, 2, 3] exploit a set of orthographic views or 2D images to reconstruct the 3D information of the object in an alternative mode.

The acquired data (usually a set of point clouds) is then processed to generate a mesh; during this step, additional operations, like point clouds filtering and merging, are usually performed. The mesh, composed by a number of triangles, is subsequently segmented in multiple isolated regions. Each separate set of triangles is later classified: its geometrical properties are analysed, and the region is associated to a geometric feature (e.g. cylinder, plane, thorus, etc.). The information obtained in the classification step determine the choice of a set of mathematical features that are tailored to the mesh in a subsequent step, minimizing a fitting error. This is the key-operation of the whole RE process and the way it is carried out heavily influences the final CAD model reconstruction.

Lastly, post-processing operations are performed to stitch together the generated surfaces and the final CAD model is created.

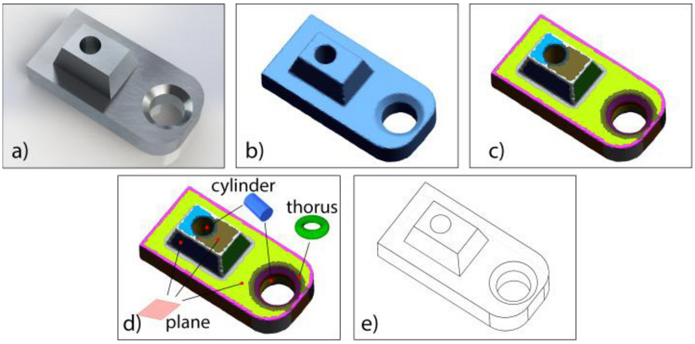

Fig. 1. RE Framework. a) Physical part; b) 3D data acquisition; c) mesh segmentation; d) classification of segmented regions; e) reconstructed CAD model.

The above mentioned steps are shared, to a certain degree, by all RE existing approaches; therefore, a number of procedures and algorithms responsible for each step have been already deeply studied and tested in literature. Hereby, a few basic considerations regarding the most important aspects of the first phases of the RE process are provided. With respect to the acquisition phase, the user typically needs to acquire multiple point clouds to successfully describe objects with elaborate shapes. A single point cloud (necessary in latest steps) is usually obtained thanks to registration algorithms, the most famous one being the *Iterative Closest Point (ICP)* algorithm. Typical problems that need to be taken into account in this step are the non-uniformity of points and the asymmetry of the scan data; both these problem can be dealt with using an appropriate defined minimizing function, such as the one presented in [4]. Registration is usually followed by sampling, which aims at obtaining a single point cloud with a uniform distribution; if reconstruction strategies exploiting curves directly derived from the points cloud are applied, as in [5, 6], this step can be ignored.

The subsequent step, called "triangulation" [7], is usually obtained thanks to well-known and established techniques, such as the Delaunay algorithm. Considering the segmentation step, which subdivides the mesh in group of triangles with similar geometric features, a review of techniques is presented by Di Angelo and Di Stefano in [8]; in the article, a number of segmentation methods are applied to meshes obtained scanning real parts. It is worth mentioning that the literature describing point clouds and mesh operations (i.e. acquisition, sampling, segmentation, classification) has been developed rather extensively and, as previously suggested, each step is usually executed thanks to well-known golden standard techniques (a detailed review of most important methods can be found in [9]). As a consequence, in the following sections, this article will particularly focus on the description of the so called "fitting" step; this phase is arguably the most important of the RE process, its execution directly conditioning the accuracy of the final CAD model. Moreover, the fitting step is probably the least and most recently studied [10].

In detail, two main categories of RE strategies are available to designers thus identifying the current state of the art. A first class of approaches can be recognized in methods and algorithms that, starting from the acquired 3D data, try to obtain, automatically or semi-automatically, the final CAD model. This approach, although fast and convenient under many aspects, generally leads to imperfect CAD models, usually expressed in formats not directly usable in most common CAD software packages.

A second approach to the problem is represented by RE processes that rely mostly on user-guided tools. These strategies exploit the designer' knowledge and engineering skills in order to assure a more controlled process and, possibly, a model closer to its original design. On the other hand, these require competent and trained users involved in rather long and complicated processes. Moreover, to be efficient, these approaches heavily relies on a CAD-like modelling environment and therefore, user-guided RE tools are principally available in well-known commercial RE software packages.

Recently, significant improvements have been made in both of the presented areas, aiming at the development of algorithms, methods and tools to develop an effective RE process. To identify limits and trends of most-recent RE tools available to designers, a study of the state of the art of both automatic and user-guided approaches is therefore presented.

3 Automatic and Semi-Automatic RE Strategies

A number of approaches, subsequently described, have been proposed in scientific literature to perform automatic reconstruction of a CAD model, starting from the acquired 3D data; notable differences among the approaches are usually mainly located in the previously described fitting step. With this respect, the most direct and easy-to-implement method exploits the information obtained in the classification step (i.e. recognized surfaces, that should make up the mathematical model) to perform a direct and separate fitting of each analytical surface to the corresponding scanned data; the final CAD model is obtained finding the set of surfaces that minimizes a defined fitting error. A notable example of this technique is provided in [11], by Bénière et al.; in the article, a method to perform the reconstruction of B-REP models starting from a 3D mesh not affected by error, is presented. The strategy relies on the fitting of independent geometric primitives (i.e. plane, sphere, cylinder and cone) to segmented data. The approach covers three steps: 1) mesh segmentation and primitive extraction (based on differential geometry operators); 2) reconstruction of relationships between primitives and 3) B-REP creation.

This strategy, although rather straightforward, presents some limits: CAD models generated with this approach are usually affected by defects, due to errors introduced during the acquisition and the reconstruction; typically, models obtained with this technique are poor representations of the object original design.

In fact, it is essential in practically every engineering application, to flawlessly reconstruct at least a subset of geometrical features and dimensions that are directly responsible for the functioning or fitting of the part. Even though the presented strategy (i.e. separate fitting of analytical surfaces) does provide the best mathematical representation possible of the scanned data, it is generally more meaningful to use a method that provides a result that somewhat diverges from the measurements, in order to retrieve a higher level of design intent.

The *constrained fitting* technique [12, 13, 14, 15] is one of the reconstruction approaches that partially sacrifices the adherence between surfaces and scanned data in favour of a closer representation of the ideal design of the part. This is achieved by imposing constraints in the fitting step, actually transforming the previously described unconstrained minimization into a constrained one. This approach allows the reconstruction of a model dimensionally faithful to the scanned data as long as respectful of a set of significant constraints. Typical constraints that are usually imposed are geometric relations between features (e.g. parallelism of planes, orthogonality between axis, symmetries or pattern regularities of features, etc.) or significant dimensions.

Different algorithms performing *constrained fitting* can be found in literature. In some cases, the constraints are detected automatically by an apposite procedure [14], analysing the relations between the identified surfaces, measuring parameters and confronting them with a set of threshold values. As an examples, two planar surfaces forming an angle of 89.9° could be detected as orthogonal and their relation would be imposed. Other methods rely on the user to impose conditions and constraints in the fitting step [12], using point-and-click graphical interfaces or other types of UIs.

Once that the constraints are defined, an optimization is automatically performed, and the final set of surfaces parameters, minimizing the fitting error under the conditions imposed by the constraints, is identified.

Werghi et al. present in [12] one of the first approaches to *constrained fitting*; in their work, a CAD model is reconstructed starting from segmented range data. The authors manually impose geometric constraints as non-linear equations in the fitting of a set of analytically surfaces; a Levenberg-Marquardt algorithm is responsible for the minimization of an objective function, which is defined by two contributes: 1) the fitting error between surfaces/data, expressed as a function of the surface parameters and 2) a weighted sum of the imposed constraints. It is important to highlight that, due to the presence of the set of weights, the constraints are imposed only up to a certain tolerance in this method; this is rather common in *constrained fitting* techniques, due to the numerical problems and complexity that a constrained optimization with perfectly imposed constraints introduces.

Wang et al. discuss in [13] an extension of the method presented in [12]; the authors perform a constrained optimization, based on [12], to fit a set of quadratic surfaces to segmented 3D data. Moreover, their method includes a feature-based reconstruction step, which recognises CAD features (i.e. extrude, revolve, sweep and loft modelling operations) in the segmented mesh and evaluates a set of parameters to fit the identified solids to the 3D data. An example of a CAD model obtainable with this approach is represented in fig. 2.

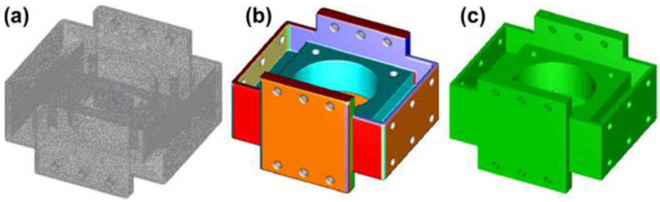

Fig. 2. Model reconstruction of a mechanical part by Wang et al. [13]. a) Original point cloud; b) segmentation result; c) reconstructed model.

Benko et al. presented in [14] a slightly different *constrained fitting* approach, applied to both 2D and 3D applications. The method hypothesizes a previous automatic recognition of the constraints to be imposed, with a methodology similar to [16]; the optimization is carried out with a methodology similar to the one previously described. Both these methods [12, 14] attempt to perform an automatic reconstruction of the CAD model and generally achieve a good representation of the original design intent. The authors state that the introduction of constraints surely improves the retrieval of the ideal geometry of the studied part; furthermore, in a number of tests, also the dimensions result closer to their original values.

As previously described, constraints are usually imposed within a tolerance in the fitting of the surfaces to the scanned data and are, therefore, only approximately enforced, even if the designer is certain of their presence in the CAD model and of their significance. Actually, errors and imperfections introduced by this approximation have a partial influence on the dimensions of the model, in some cases being practically inexistent, but can compromise the model usability in following applications.

This is a central problem in engineering applications, particularly important since all the mentioned techniques (and generally all the automatic and semi-automatic approaches) usually produce non-parametric CAD models (e.g. STEP, IGES, B-REP representations) that do not contain any information about the part modelling history. Hence, an *automatic feature recognition* step is usually performed by the designer, within a chosen CAD environment, to convert the previous non-parametric model into a parametric one. Unfortunately, the *automatic feature recognition* step efficacy is negatively influenced by the imperfections originated in the previous *constrained fitting* step, especially by loosely imposed constraints. As a consequence, this additional step, heavily inhibits the general efficiency of the presented framework and has limited the applicability of automatic and semi-automatic RE approaches.

Summing up, an accurate recognition of features, the definition of an exact modelling tree, and the achievement of a meaningful final CAD model, although fundamental elements in engineering applications, are rather difficult to obtain, especially with an automatic approach, despite the number of scientific works dealing with this topic.

4 User-Guided RE Tools

User-guided approaches represent, nowadays, the category of RE methods most used by designers. This is due to the limitations of automatic approaches, described in the previous section, which make this approach the most reliable to reach a satisfying result (i.e. a parametric CAD model as faithful as possible to the original design intent). In this framework, in fact, the designer is in control of the whole process and can build a model that reflects his/her knowledge of the part function, fitting and original design.

It is important to note that the efficacy and usability of user-guided tools highly depends on the "hosting" environment in which are implemented; in particular, most effective RE tools require a proper CAD-like software environment, provided with 1) parametric solid modelling capabilities and 2) scanned data/mesh handling features. In view of that, advanced RE tools can be found mainly in a limited number of well-known commercial RE systems. Chang and Chen presented in [10] a description of the state of the art of commercial RE systems; their study covers several software packages and focuses on parametric modelling. The present work, using their conclusions as an input, provides an up-to-date description of the current research.

CAD and RE modelling tools are generally comparable: on a basic level, both allow the user to generate analytical surfaces; RE tools, however, usually permit to extract useful information from the scanned data to consequently generate guided surfaces and geometric features.

Basic RE functionalities, available in most systems, are limited to the fitting of a geometric feature/surface to the scanned/segmented data. In this case, a subsequent manual stitching of adjoining surfaces is performed to generate the CAD model. In most low-level systems, the resulting model is not parametric and, therefore, cannot be modified once that the reconstruction process is finished. Another limit of these systems is represented by the available types of surfaces/features in the system: the majority of systems permits the creation of simple primitives (e.g. cylinders, spheres, etc.) or NURBS patches, particularly useful for the reconstruction of freeform surfaces. More advanced systems allow the fitting of more refined surfaces, as extrusion and revolution surfaces.

Full-parametric tools, on the other hand, are available only in most advanced RE software packages; parametric sketches and geometric features, modelling feature tree, and the possibility of drawing sketches directly using information provided by the scanned data are among the most advanced RE tools currently available to designers.

In advanced RE systems, the reconstruction follows the steps outlined in section 2; the scanned mesh is imported in the modelling environment, segmented and the various mesh regions are classified; afterwards, a convenient reference frame, aligned accordingly to the mesh most significant geometric features, is identified and used to guide all subsequent modelling steps. An important feature, recognizable and dimensionally relevant, is usually chosen to begin the reconstruction; all subsequent features are generated using the reference frame and the main feature as landmarks (Fig. 3).

The most interesting capabilities and tools are offered in specialized RE software packages; with this respect, notable examples are Rapidworks® (a Nextengine proprietary version of Geomagic Design X®, formerly Rapidform XOR3®) and Polyworks®.

Rapidworks®, in particular, provides a full-parametric modelling environment and offers all the functionalities previously mentioned, the most important being: 1) fitting of primitives, revolution or extrusion surfaces and NURBS patches to the scanned data; 2) loft/sweep surface fitting; 3) possibility of imposing a single geometrical constraint in the creation (i.e. in the fitting step) of some types of surfaces and features (e.g. axis direction in revolution/extrusion wizard); 4) 2D parametric sketching guided by mesh sections; 5) a solid modelling environment directly linked to a traditional CAD environment (i.e. Solidworks®), allowing for fully editable and directly spendable models.

Polyworks® offers similar functionalities: the software, as an example, provides parametric sketches that can be drawn upon the mesh data; the system, however, does not offer 3D parametric solid modelling capabilities and the sketches must be exported into an external CAD system in order to perform subsequent 3D modelling operations.

In addition to proper RE systems, a number of commercial CAD software packages offer useful tools as well to perform CAD reconstruction. Their functionalities, even if not specifically RE-oriented and generally not the most advanced, are to some extent comparable to those previously described. Although their modelling tools perform flawlessly, the performances of these systems are usually limited sensibly in the interaction with mesh/scanned data; as an example, mesh-guided sketches are not available.

Among the CAD systems tested by the authors, Siemens NX® and Leios2® prove to be the best equipped to fulfil RE needs. Both these systems provide a parametric 3D modelling environment, and allow the fitting of a set of simple primitives to the scanned data. Moreover, for certain primitives is possible to enforce a single geometrical constraint (e.g. a relation of orthogonality or parallelism between axes) during the fitting; this feature, also available in Rapidworks® as previously mentioned, allows the exact imposition of known constraints in the reconstruction, generating more meaningful models. Regrettably, advanced geometrical constraints cannot be imposed with these tools and their usefulness is, therefore, limited.

Summing up, user-guided RE tools, mostly available in commercial RE and CAD software systems, permits the reconstruction of CAD models by means of parametric modelling tools; the introduction of parametric models increases the final CAD usability and its usefulness for the designer, making the previously mentioned "*automatic feature recognition*" step redundant. The creation of the model is generally achieved by means of a series of independent fitting steps: in this framework (fig. 3), every feature previously identified is manually and individually generated, one feature at a time. Regrettably, the established feature creation chain imposes higher uncertainties on the last features generated, which are negatively affected by previous errors and wrong choices of the designer.

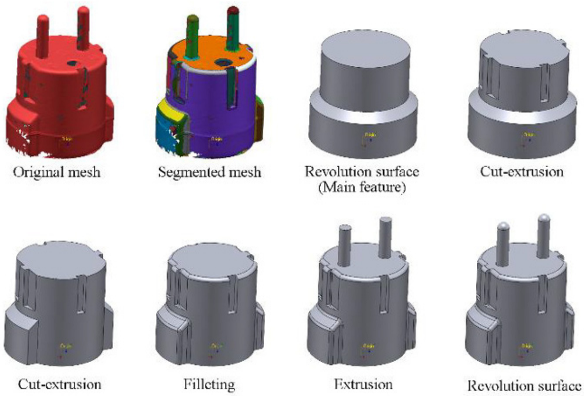

Fig. 3. Sequential steps of the reconstruction process of an electrical socket adapter

Regarding the level of design intent retrievable with this approach, geometrical constraints can generally be imposed in the process in a limited number and up to a certain level of complexity, allowing for models more faithful to the original design intent of the part. Sadly, this framework, although highly reliable and assuring an overall better result with respect to automatic RE approaches, relies on a competent user and a time-consuming framework.

5 Conclusions

In this paper, a series of practical approaches to CAD reconstruction were briefly reviewed. Two main RE strategies were identified and discussed: the automatic/semi-automatic approach and the user-guided approach. Both the approaches rely on the same underlying framework and therefore exploit similar "ingredients" to perform the reconstruction. Automatic methods generally provide a fast and easy-to-perform solution to the RE problem; obtained models, however, are affected to a certain degree by imperfections and are usually non-parametric representations. For these reasons their usefulness to designers is rather limited.

User-guided methods, on the other hand, require a competent and trained user to be applied, but allow the retrieval of a CAD model faithful to the original design intent in terms of geometry and dimensions.

The user-guided approach is, arguably, the most used by designers nowadays, mostly due to the possibility of obtaining a parametric model directly at the end of the process. Future research, addressed to the development of a streamlined process and of tools capable of imposing advanced geometrical constraints, could further increase benefits of user-guided methods.

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